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Relativistic motion and spatial characteristics of radiation from an electron driven by an intense few-cycle laser pulse

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ABSTRACT

Relativistic motion and full spatial characteristics of radiation from an electron driven by an intense few-cycle laser pulse have been investigated theoretically and numerically with a single electron model. It is discovered that the influence of the initial phase on the process of relativistic motion and spatial characteristics of the radiation is apparent for intense few-cycle laser pulse. The characteristics can be used to measure the initial phase of intense few-cycle laser pulse in experiment.

1. Introduction

With ultrashort pulse high-power lasers it has become possible via strong focusing to extend the irradiance to levels to 10^{18} W/cm^2 and with petawatt level lasers intensities much higher than this may be achieved [1]. In the intense laser field, the electron dynamics becomes highly relativistic and then many nonlinear effects start playing a role in the nonlinear scattering process [2–13]. Further, the radiation generated by relativistic electrons is also frequency up-shifted by the relativistic Doppler effect [4]. In addition, He et al. [5] discussed the influence of the electron initial conditions, such as the electron initial position or initial time injecting to the laser field, on electron dynamics and radiation. All the above works treat the laser field as a plane wave approximately. Lee et al. [6] extended the above analytic investigations of nonlinear scattering to the multi-cycle laser pulse case. They investigated the temporal and spectral characteristics of nonlinear scattering in the laser pulse with duration of 20 fs, and their numerical results agree well with the analytic studies in the plane wave case. The foregoing works focus on the scattering in continuous plane waves or multi-cycle laser pulses. Now, ultrashort intense laser pulses with durations less than 5 fs are available as research tools. In this case, the laser pulse contains about two optical cycles, the laser intensity varies almost as rapidly as the laser oscillations and the time variation of the electric field depends sensitively on the initial phase of the few-cycle laser pulse. Due to these properties of few-cycle pulses, many novel and attractive phenomena in laser – atom interactions, such as photoionization and high harmonics generation, have been demonstrated theoretically and observed experimentally in the few-cycle regime. The full spatial characteristics of the radiation in the cases of few-cycle laser pulse did not receive enough attention in previous studies. Such is one of the aims of the present paper.

In this paper, we present relativistic motion and full spatial characteristics of radiation from an electron driven by an intense few-cycle laser pulse. Our results show that the radiation from an electron in a few-cycle laser pulse shows many different characteristics in contrast to the plane wave and multi-cycle pulse cases. For most initial the well-known symmetry of the radiation angular distribution is broken in the few-cycle regime. These phenomena are illustrated from the electron dynamics and properties of the few-cycle pulse.

2. The interaction model and formulation

For a Gaussian linearly polarized few-cycle laser pulse, the vector potential can be expressed as:

$$\mathbf{a}(\eta) = a_0 \exp\left(\frac{-\eta^2}{2L^2}\right)\cos(\eta + \Theta)\mathbf{x} \quad (1)$$

where, a_0 is the peak amplitude normalized by mc^2/e, $\eta = z - t$, $L = d/2$ and d is the laser pulse width. Θ is the initial phase of the laser pulse. Θ is different from the initial phase that electron experiences when it enters the field. In the above definitions, space and time coordinates are normalized by k_0 (wave number) and ω_0 (laser

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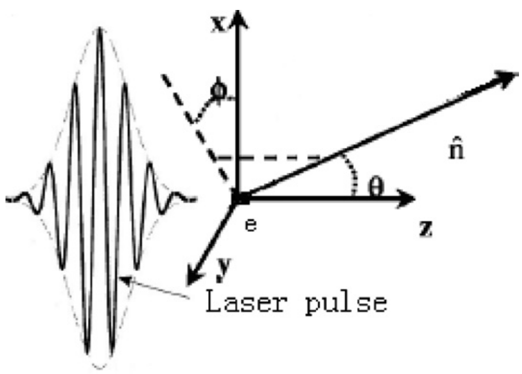

Fig. 1. Schematic diagram showing the interaction of an incident few-cycle laser pulse with a stationary electron, we assume the laser field propagation along $+\hat{\mathbf{z}}$ axis.

frequency) respectively. m and e are the electron mass and charge, respectively.

The schematic geometry of few-cycle laser – electron interaction is depicted in Fig. 1. Here, we assume that the laser pulse propagates along the $+\hat{\mathbf{z}}$ axis and an electron is initially stationary at the origin of coordinates. The radiation direction is $\mathbf{n} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}$ (Fig. 1). In this expressions θ and ϕ have the usual meanings as per the spherical coordinate system with the $\hat{\mathbf{z}}$ axis aligned along the electron longitudinal motion.

The motion of an electron in an electromagnetic wave is described by the Lorentz equation [13]

$$d_t(\mathbf{p} - \mathbf{a}) = -\nabla_a(\mathbf{a}\cdot\mathbf{u}), \tag{2}$$

together with an energy equation

$$d_t\gamma = \mathbf{u}\cdot\partial_t\mathbf{a}, \tag{3}$$

where $\mathbf{u}$ is the velocity of electron normalized by c, $\mathbf{p} = \gamma\mathbf{u}$ is the normalized momentum, $\gamma = (1-u^2)^{-1/2}$ is the relativistic factor or normalized energy, and the ∇_a in (2) acts on $\mathbf{a}$ only. Note that Eqs. (2) and (3) are the exact one.

As the solution of 1D wave equation, the normalized vector potential $\mathbf{a} = \mathbf{a}(\eta)$. The quantities describing electron motion are assumed to be functions of η as well. With $\partial_z = \partial_\eta$ and $\partial_t = -\partial_\eta$, one gets from (2) and (3)

$$\gamma\mathbf{u}_\perp = \mathbf{a}, \quad \gamma(u_z - 1) = \varepsilon, \tag{4}$$

$$\gamma = \frac{-(1 + a^2 + \varepsilon^2)}{2\varepsilon} \tag{5}$$

where we have assumed the transverse velocity $\mathbf{u}_\perp = 0$ when $\mathbf{a} = 0$, ε is a constant of the motion to be determined by the initial conditions on the electron motion. The motion of the electron can be fully determined; the velocity and displacement can be expressed as functions of η

$$\mathbf{u}_\perp = \frac{\mathbf{a}}{\gamma}, \quad u_z = 1 + \frac{\varepsilon}{\gamma}, \tag{6}$$

$$r_\perp = \frac{1}{\varepsilon}\int \mathbf{a}\,d\eta, \quad r_z = \frac{1}{2\varepsilon^2}\int(\varepsilon^2 - 1 - a^2)d\eta, \tag{7}$$

where $r_\perp$ and r_z are the transverse and longitudinal displacement of the electron, respectively.

Electron in relativistic motion emits radiation, the radiated power per unit solid angle is given by [12]

$$\frac{dP(t)}{d\Omega} = \left[\frac{\left|\mathbf{n}\times[(\mathbf{n}-\mathbf{u})\times d_t\mathbf{u}]\right|^2}{(1-\mathbf{n}\cdot\mathbf{u})^6}\right]_{t'}, \tag{8}$$

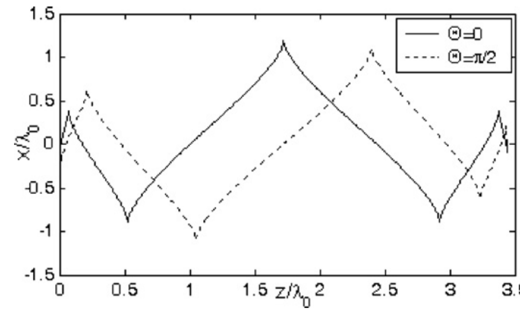

Fig. 2. The trajectories of an electron during the few-cycle laser pulse for different initial phase $\Theta = 0$ (solid line) and $\Theta = \pi/2$ (dashed line). The laser amplitude $a_0 = 1.0$, pulse duration $d = 2\lambda_0$ (corresponding to 6.6 fs).

where the radiation power is normalized by $e^2\omega_0^2/4\pi c$ and t' is the electron's time or retard time. The relation between t' and t is given by

$$t = t' + R, \quad R \sim R_0 - \mathbf{n}\cdot\mathbf{r}, \tag{9}$$

where R_0 is the distance from the origin to the observer and $\mathbf{r}$ is the position vector of the electron. Here the observation point is assumed to be far away from the region of space where electron acceleration occurs.

3. Results and discussion

We begin by looking at the motion of the electron from the point at which it is overtaken by the front of the few-cycle laser pulse until

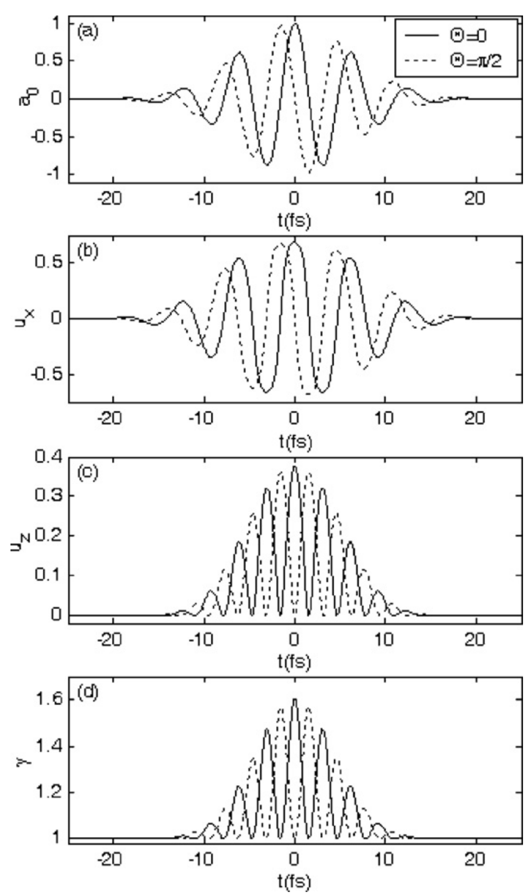

Fig. 3. (a) The vector potential of the few-cycle laser pulse, (b) the electron's transverse velocity, (c) longitudinal velocity and (d) normalized energy of an electron during the few-cycle laser pulse. The other parameters are the same as in Fig. 2.